INTEGRATED, COMPUTER-AIDED DESIGN OF AIRCRAFT

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ABSTRACT

The design process for conceptual, preliminary, and detailed design of aircraft is discussed with emphasis on structural design. Problems with current procedures are identified and improvements possible with an optimum man-computer team using integrated, disciplinary computer programs are indicated. Progress toward this goal in aerospace and other industries is reviewed, including NASA investigations of the potential development of Integrated Programs for Aerospace-Vehicle Design (IPAD). The benefits expected from IPAD lead to the conclusion that increased use of the computer by a man-computer team that integrates all pertinent disciplines can create aircraft designs better, faster, and cheaper.

INTRODUCTION

Current requirements to produce technically superior aircraft at lower cost force the generation of optimized designs of greater technical depth in less time than in the past. Automation of the design process via computer-aided design systems that integrate all the pertinent disciplines can provide a solution to this problem. In this paper I will present a philosophical discussion of why we should automate the design process, how far we have come, and where we should be going. It is the result of several years of observation and participation in the automation of analysis and design of aerospace vehicles, particularly on structures.

This paper starts with a discussion of the current design process and suggests the needs and payoffs from automation. Brief definitions of design automation and integrated computer-aided design are included. Then the nature of the design process is reviewed and followed by a description of progress already made toward automated design. Some additional steps toward greater automation, now in the planning stage, are described and their potential benefits are indicated. Finally, a few concluding remarks are presented.

The opinions presented in this paper are my own and do not necessarily reflect those of NASA. Because of my personal experience in structures, the discussion will be biased toward structural design, but the total aerospace vehicle design process will be considered.

THE NEED FOR AUTOMATION

Interest in computer-aided design is a logical consequence of the increasing cost and complexity of aerospace vehicles and systems and the related increase in the size of design staffs and in the complexity, cost, and time required for design, Reference 1. One of the factors contributing to both development and unit cost is the cost of design, which is increasing as illustrated in Figure 1. The cost of manpower and computer time required in a typical airplane company for designing one pound of aircraft structure is plotted against calendar year. It shows that we are paying about four times as much today for manpower as for computer time. Is this the best use of our available resources? I think not. Computers should have a larger share. If these trends continue for about a decade, expenditures for structural design will be equally divided between men and computers. However, I believe the trends will change and total design costs will grow less rapidly as we make more and better use of both men and computers. Hopefully, total costs could level off or turn downward in the future, but this is unlikely.

Another aspect of design that affects vehicle cost is illustrated in Figure 2 where planned and actual vehicle costs are plotted against time to design and manufacture a prototype. The vehicle cost increment is due to untimely engineering that produced results too late, caused out-of-sequence and repeated work, and resulted in unnecessary manufacturing changes. The cumulative effect is a magnified cost increment. Untimely engineering occurred because some phases of the design process did not go into adequate technical depth and/or because human limitations to deal with the volume and complexity of information involved were exceeded. A strong need exists to reduce human activity by providing some computer assistance on all routine functions and to use computerization to add greater technical depth and optimization in the early stages of design where basic concepts are selected.

Problems with the current design process are summarized on Figure 3. They arise from the characteristics of advanced aerospace vehicles, the nature of the design process, and the big design staffs required for such vehicles. The problems stem from the increased size, sophistication, performance, and sensitivity of new vehicles which increase everything related to the design process. Of particular concern are the longer and longer times required to design an advanced vehicle. Not only does this time increase costs in many ways, it also makes the vehicle development cycle unacceptably long with the danger of introducing obsolete products into the market. Risks of poor quality and/or high costs are great.

In addition to many design requirements, conditions and criteria, and a multitude of data that must be generated, analyzed, and communicated, large numbers of people, that must work together as a team, are involved. The result is a large organization that operates in a complex manner, is difficult to manage, and which of necessity takes a long time to get its job done properly. The size of the product, the number of design conditions and the amount of data will continue to increase; therefore, time and money can be saved only by changing the process so that fewer designers can do their thing faster. This is where automation can help; the computer must be used to do all things, that do not require unique human traits, faster (and better?) than man. Design flow time can be reduced with secondary benefits in reduced costs (time saved is money saved) and increased design quality. Fortunately, design technology and computer hardware and software have reached a state where much of the design process can be automated in the next decade.

The growth of automation in aerospace vehicle design – past and future – is shown in Figure 4. It traces the growth of automated structural analysis from elements to complete vehicle capability, the emergence of automated structural design and its development to a mature technology within this decade, and the prospect of automated vehicle design growing rapidly from the embryonic systems now being used. The last 20 years brought about a revolution in structural analysis through computerization. For the vantage point of 1985 or 1990, we will see that a similar revolution has occurred in design.

Automation of the total airplane design process can occur in an evolutionary manner in which the design organization and computer programs are modified in steps. The first steps will be to use the computer as a communications link between the players, gradually programing more and more human activity of a routine nature for the computer, then extending automated synthesis capability to the total vehicle. By this time it will be apparent that some fundamental changes in procedures, organization, and man-machine relationships are necessary, Reference 2. Hopefully, enough research on the design process, both its technical and social features, will have been done so that revolutionary changes can appear with a new generation of managers, designers, computers, and software. The process that results will be vastly different from what we have today in the tools, people, training, and organizational concepts, References 1 and 2.

The words design, integrated, computer-aided, and automation have been used rather freely, so I will present now the definitions I will use in this paper. I am equating automated design to computer-aided design, and using them interchangeably, to indicate that this is the best combination of men and machines for designing a product. It can involve several levels of computerization that will change with circumstances and time. The machine is the digital computer and all types of devices, apparatus, or machines that can be operated with or from it to aid the design process. The design process encompasses all activities required to generate the data needed to produce a product and therefore covers a wide scope of technical disciplines ranging, for example, from aerodynamics to noise to structures to manufacturing to economics. Integrated refers to how the many computer programs used in the design process work together. An integrated system provides for the greatest interaction and flexibility in program utilization and the highest potential for automation without loss of the insight and innovation that only a human designer can provide. In addition, an integrated system can provide for an intelligent dialog between the designer and the computer, partners that augment and complement one another in managing and accomplishing the design task.

THE DESIGN PROCESS

The process used to design any product is basically simple, Figure 5. Someone sets down a requirement, the designer finds an acceptable configuration that satisfies it, and then generates the data required to fabricate the product. The selection of the appropriate configuration is not simple, however. The designer will first select one that he thinks, from experience, will meet the need – this is the idea and innovation stage. Then he analyzes it to determine the characteristics of his product and compares these with the characteristics allowed or required of it – the analysis stage. Initially, the product will lack some essential characteristics so it must be changed – this is the decision stage which requires insight and experience. However, analysis of the effects of design changes on product characteristics can assist the designer in his decisions. Next, the designer goes through several cycles in which the product is reconfigured and reanalyzed until all required characteristics are obtained in the final configuration. Then, all data needed to fabricate the product are compiled and sent to the shop. Of course, manufacturing methods and costs were a factor in the design evolution from the beginning.

The various blobs in Figure 5 represent work to be done or tasks. The arrows represent the flow of data or information. Tasks and data are the elements of the design process which is a data management activity – the generation, flow, and processing of data are all that happens in design. Of course, this data management activity is carried out by people and machines working in an organization. If the organization required to design a product is small, the management of the information flow is not difficult. A large design organization is another story.

Figure 6 is a cartoon of the current design procedures used for large airplanes such as a wide-body jet transport. It shows men and machines in the same information flow as in Figure 5. But this chart shows that much of the data flow only because one guy hands it to another. This is not good. The design organization for a large airplane includes more than a thousand people at its peak, involves numerous individuals that are designers, and has large numbers of analysts, draftsmen, test engineers, technicians, administrators, and other specialists. A few simple calculations of the combinations of personal contacts required in a group of this size reveal the staggering magnitude of the person-to-person communication problem in giving and receiving data and decisions in a highly interactive situation like multidisciplinary design. For example, if only 50 people on the staff must talk to each other periodically, then 1225 conversations are required in each period (with 100 people the number rises to 4950). Big design organizations, then, usually manage data flow inefficiently. They should look to automation to speed up this part of the process by reducing the number and duration of human contacts. The largest gains from automation probably will be in the big organizations with the big problems, however, any design organization can benefit. In addition, further automation of analyses and other tasks will also speed the design process, particularly in automating methods for rapidly resizing or reconfiguring a vehicle or component that does not satisfy its design requirements.

The design process has important time and phasing characteristics suggested by Figure 6 but not apparent in Figure 5. Figure 7 extends Figure 5 into the time domain to illustrate the sequencing and cycling that occurs as the design progresses. Note that each activity occurs intermittently. If each is performed by a particular specialist, his assigned task will not be completed in one work period and he will have to be reoriented each time it comes around again. Continuity of tasks is often achieved in design practice by simultaneously working tasks that ideally should be done in sequence. Then, individual specialists could be working simultaneously at different design levels on the same project with the danger that much effort may be wasted. The problem becomes more acute on multidisciplinary airplane projects wherein aerodynamics could be several configurations ahead of structures. All disciplines should work approximately in-phase to produce a technically balanced design in each cycle. Automation can help achieve this goal by reducing the time required for each task and by speeding the flow of data between activities and disciplines.

The design process passes through several stages or levels as it progresses from an initial concept to the final details. Figure 8 is a diagram of the development of an aerospace product that shows the place for design. Continuing activity in research, development, and marketing periodically identify new concepts and technology with sales potential. This idea enters a conceptual design phase to scope its characteristics and, if attractive, moves into a preliminary design phase where it is worked to greater depth. When the design is sufficiently mature, management authorizes the product go-ahead and detail design, manufacturing, and testing lead to first product delivery. Design support for the product in production is a continuing activity to cover changes and modifications in future product improvement. This total process involves many subtasks and cycles in a variety of sequences over a long period of time. The needed automated design system must encompass this total process and the multitude of functions contained therein.

Design networks can be drawn of processes depicted in Figure 8 to any level of detail required, but they soon become exceedingly complex. Figure 9 goes one step in that direction by expanding the preliminary design phase and indicating major decision points and recycling routes. The preliminary design phase is divided into sizing the product to the marketing criteria, refining it by applying more powerful analyses, and verifying it by more rigorous analyses and selected tests. The design is then reviewed to determine if construction should proceed. Note that at each decision point before go-ahead, the process may recycle to as early a level as appropriate. However, once it enters detailed design the major system parameters are fixed and any problem that arises must be solved within that subsystem. Therefore, preliminary design must produce a thoroughly satisfactory configuration for the total system adequate in all subsystem characteristics, including fabrication costs, if a successful product is to result. Not only must our automated system accommodate the requirements of each of these levels and decisions, it must also insure adequate technical depth at each level (especially in preliminary design) within the time and cost available.

Design levels have been discussed without defining them in detail; Figure 10 attempts an approximate definition. Each organization utilizes different definitions and process within its design organization so Figure 10 is an amalgamation of several sources. The levels are defined in terms of the manpower, flow time, and number of configurations examined. The accuracy of weight estimates and short descriptions of the objectives and product are included too. All numbers are approximate because of the variability of scope of a design project, ranging from a small fighter aircraft to a large supersonic bomber or transport. Again note the key role played by preliminary design; only one overall configuration goes into detail design, however, many components and parts will go through several design iterations in this design level.

DESIGN SYNTHESIS AND OPTIMIZATION

Diagrams of the design process discussed above (Figs. 5, 6, 7, and 9) have shown cycles in which the design must be reconfigured because it did not meet some criteria. Resizing the total configuration or one of its parts can be done by trial and error, but systematic approaches called design synthesis are more productive. Synthesis includes optimization since the objective is to attain a maximum or minimum value of some merit function. Structural synthesis, for example, is often discussed under titles such as minimum-weight design and structural optimization. It has not been used enough in design although it has been available for over 20 years, References 3 and 4. Its use, however, is increasing.

Some general comments on design synthesis are appropriate here.

1. The synthesis approach provides a systematic way of conducting analyses used in design to reach the best configuration with a minimum of time and effort. Synthesis techniques must, therefore, be an important part of any automated design system.

2. Synthesis can, at least theoretically, be applied to the total system as well as to small parts, but it is most useful for sizing the elements of a vehicle where less innovation is expected than in the formulation of system concepts.

3. Synthesis of most parts or systems of practical interest is too complicated for closed-form solutions. The use of a computer is essential. Therefore, synthesis is essential in automated design and synthesis of complex parts is impractical without automation.

The computer finds the optimum solution to a synthesis problem in either a direct or indirect way, References 5-7. The direct approach, exemplified by mathematical programing, makes an intelligent and systematic search among the design variables to locate the minimum value of its objective which may be weight, cost, or other considerations. This method is general but is usually expensive if large numbers of variables or complex analyses are involved. The indirect approach uses optimality criteria that are expected to produce the desired result, at least within engineering accuracy. Such procedures are relatively fast, they can handle large numbers of variables readily and are practical for design of large structures. Both approaches are needed for automated designs of vehicles systems; however, considerable additional development is required for application to multidisciplinary situations.

The application and strategy of optimization in aircraft design synthesis is summarized in Figure 11 for the three design levels. In the conceptual and initial preliminary design phase (sizing) the total system or configuration can be optimized with respect to a few key parameters. Subsequently, optimization must be limited to subsystems. However, subsystem inputs to configuration optimization must be in sufficient technical depth to accurately reflect the effects of subsystem changes on configuration parameters. The types of parameters optimized in each level are indicated for wing design as an example.

The number of parameters increases greatly as the designer goes into more detail. Judicious choice of the parameters to be optimized in each cycle or level is important. The designer cannot afford to dissipate his resources on optimization of secondary parameters. To take an extreme example, why optimize rivet size and spacing if the wing aspect ratio is still being varied?

The total system is designed at the conceptual level where ideas and innovation are essential whereas elements are of concern in the detailed levels. On the other hand, parameter optimization in the conceptual phase may be inaccurate because the analyses used are not of sufficient depth to include detailed design parameters that could affect some of the primary parameters. I am thinking, in particular, of the flutter problem which involves the integrated effect of many structural and aerodynamic parameters, some of which may be frozen before a comprehensive flutter analysis can be made.

Optimization strategy also varies with design level and three approaches are indicated. The mathematical approach uses the processes discussed above; it is useful at all levels. Trade-off studies explore a range of solutions around a local optimum to determine sensitivity to changes before committing to a specific arrangement. Sequential refining is the application of more accurate analytical modeling without formal mathematical optimization processes, but these refined analytical models can be subjected to mathematical optimization and trade-off studies, also.

Incorporation of optimization procedures into an automated design system imposes several requirements in addition to the basic technical, search, and mathematical capabilities. The user must have great flexibility in the way he sets up each particular task. He must be able to specify the merit function and the constrained and independent design variables he desires. He must have great freedom of choice in the execution sequence and the particular technical and optimization methods employed. He must have complete control over the computations so that he can stop the search, inspect intermediate results, modify the procedure, and start again. All this dictates that the design system must be very fast, flexible, and versatile; but only an automated system can accomplish this in a practical way.

PROGRESS TOWARD INTEGRATED, COMPUTER-AIDED DESIGN

From the discussion so far, you might get the idea that little has been done to integrate disciplines and do computer-aided design. On the contrary, computers are used extensively to do all kinds of design tasks and some rather sophisticated systems have been assembled and used. The point to be made is that we can go much, much farther.

Figure 12 lists a sampling of the code names and originators of programs in operation or under development. The list is not exhaustive, simply representative, References 8-14. Several programs with a company as originator were developed under U.S. Air Force sponsorship, for example, Reference 14. Conceptual vehicle synthesis codes are widely used. They have a highly computerized, broad, multidisciplinary base but relatively little technical depth in some disciplines such as structures. Such comprehensive systems are not now available for the subsequent design phases (preliminary and detailed) of a complete vehicle. The other examples shown are representative of progress in structural analysis and design. Some design programs size individual elements of a prescribed structural arrangement under given loads, using optimality criteria for minimum weight. Other programs integrate loads and structures, including aeroelasticity considerations, some doing primarily analysis while others emphasize structural sizing. Although NASTRAN, a large NASA program, Reference 15, is listed under structural analysis, plans for future additions include a fully stressed design module to provide some sizing capability. Similarly, other programs may be undergoing increases in scope.

The aerospace industry is not the only one that is automating the design process, Figure 13. The U.S. Army is considering a comprehensive automated design system for each class of commodity it uses. The U.S. Navy has been steadily increasing its use of computer-aided ship design and the U.S. Maritime Administration has been encouraging accelerated use of computers in commercial shipbuilding and design. In architecture and civil engineering, extensive international activity in automated design is being coordinated and fostered through technical societies, Reference 16. All this is further evidence that integrated, computer-aided design is an emerging technology, the benefits of which are widely accepted.

In general, programs for computer-aided design have been built to provide capability in one design level only. Figure 14 shows the approximate design level applicability of several programs listed in Figure 12. Note that the IPAD program, which will be discussed later, is the only one intended to cover all design levels in a single-integrated system.

The IPAD program will be described in the next section to illustrate the type of integrated, computer-aided, system design programs that can be developed today and the benefits that can be achieved. But first, let's examine two representative structures programs (IDEAS and ATLAS) that have demonstrated substantial improvements already. The structure of an aerospace vehicle contains more parts and details that require exacting design than any other subsystem. The airframe of a wide-body jet transport, for example, contains more than 1,000,000 parts. Consequently, structural analysts and designers of airplanes, missiles, space vehicles, ships, and buildings are leading proponents of computer-aided design.

Figure 15 is a simplified layout of the Integrated Design Analysis System (IDEAS) developed by the Grumman Aerospace Corporation, starting in 1967, Reference 17. IDEAS is a highly organized system of more than 70 computer program modules interrelated by data packages from a central data bank that stores all calculated data. Sequencing and execution of these modules enables the design team to plan, schedule, coordinate, and control a stream of analyses that provide internal loads, deflections, and temperatures for many subsequent analyses by several engineering groups. IDEAS is primarily used at the detail level and the flow of information in the first and subsequent IDEAS cycles is an integral part of the Grumman design organization and process. IDEAS was used to design the F-14, requiring over 2000 computer hours. This application verified their initial predictions of substantial reductions in the time and engineering man-hours required to accomplish the same tasks by conventional procedures. It is a major step forward in computer-aided analysis and demonstrates that real gains are indeed attainable. However, it currently contains only a limited, but growing, capability for design, that is, for determining allowables, margins of safety, and resizing.

The development of the IDEAS program concentrated on building interfaces between accepted analysis procedures and deliberately avoided new technology. A different approach is being taken in The Boeing Commercial Airplane Company in developing an integrated structural analysis and design system (ATLAS), Figure 16. Its objective is to integrate related structural disciplines in a common framework, applicable to most design levels, with emphasis on automated control of program flow and data communications between modules, utilizing all available computer resources to achieve "optimal" processing efficiency. Thus, ATLAS has a control module that functions like a design manager to make analysis path decisions and monitor their execution. Module development, a technically oriented language for task definition, and emphasis on automatic input data generation, are among its new technology features. The development of the analysis loop for strength design is operational and that for stiffness is nearing completion. Future additions planned include flutter design modules to resize for the next analysis cycle. ATLAS has been applied to several analysis tasks and a comparison of the time and resources required by ATLAS and by conventional methods to do the same structural analysis job on a supersonic commercial transport at the preliminary design level showed that both manpower and flow time were cut in half.

INTEGRATED PROGRAMS FOR AEROSPACE-VEHICLE DESIGN (IPAD)

The next step toward design automation in the aerospace industry is to assemble a computer-aided design program for complete vehicles or for an entire transportation system. NASA is studying the feasibility of such a system called Integrated Programs for Aerospace-Vehicle Design (IPAD), Figure 17, Reference 18. The basic software in IPAD could be used on other design projects too. The U.S. Air Force, Army, Navy, and industrial companies are participating in these studies. IPAD in the design situation will provide the software for conducting the design process with people and computers. The major software elements are the Executive, the Data Base Manager, the Utilities, and the Operational Modules. The Operational Modules are the computer codes that perform particular analysis or design functions. These programs are, for the most part, now in use but, in most present design activity, they are linked together by humans. In IPAD, programs can be linked together in the computer in any sequence desired by the designer through the Executive, which is the manager that interfaces with the user, provides him control of the process, and provides instructions for carrying out each part of the design task. The Data Base Manager and Utilities are the Executives' staff assistants that collect, organize, store, distribute, and display information, computational activity, and task sequences for effective operation and control of the process. The primary NASA goal in IPAD is the development of the IPAD core – the Executive, Data Base Manager, and Utilities. NASA will develop, also, some Operational Modules, as appropriate, but most of them will be programs already available to the IPAD user. IPAD will be constructed so that modifications required to fit existing Operational Modules into the IPAD system will be minimized.

Figure 18 gives a different overview of IPAD, shows the interrelationships between the major components, and illustrates the engineering usage philosophy. The technical management and engineering capability utilized reside in the people (managers and users) and the library of data and automated modules they have developed. They exploit their capability through a variety of computer hardware and software. The host computer has a variety of peripheral devices to facilitate user input and output and his interaction with the computer. The IPAD framework software supports and augments the capabilities of the operating system software and the automated analysis, design, drafting, and management tools of the user.

The objectives of IPAD are given in Figure 19. NASA envisions a versatile and open-ended, multidisciplinary design tool that can handle a wide variety of design situations and be responsive to the needs of the designer. The objectives are not directed toward fundamental changes in the current design process but toward better and more extensive use of the computer in existing organizations. IPAD will be structured to do any group of tasks the designer chooses with complete automation possible on tasks for which appropriate operational modules are available. The basic idea is to integrate design activity through the computer to speed up the process. Automation, in the sense discussed in this paper, will then grow as the IPAD system is developed.

Since the IPAD data bank can contain all data on the status of a design project, it can contain records and logs of all activities that have occurred and can display them and compare them with plans. Its capability in this area can greatly reduce the demand on men to maintain so many routine records. Therefore, it introduces new control features between the people and the systems within an organization and a way to achieve more accurate information and more positive communication. Thus, engineering project management may more efficiently plan, control, and communicate design information, Reference 2.

The status of IPAD is given in Figure 20. Two feasibility studies are being conducted for NASA by The Boeing Commercial Airplane Company and General Dynamics/Convair Aerospace Division with completion scheduled in September 1973. The IPAD system development plans resulting from these studies will be evaluated by NASA with assistance of the aerospace industry in the months that follow. Development of the core software of an acceptable system will begin then at a pace determined by the available resources. When a functioning IPAD system is developed, it will be released to the U.S. aerospace industry for checkout and design use. The dates on Figure 20 are the current estimate of the time required for the first level of IPAD to become operational in U.S. industry. IPAD will be a tool for U.S. industry primarily and the U.S. Government secondarily.

Operational modules will be collected and modified to function in IPAD. Some of them may be NASA computer programs (for example, NASTRAN, Ref. 15) developed in a continuing research and technology program; others may be developed to fill particular technology gaps in the IPAD approach to design. The status of computerization of the technical capability that resides in such operational modules for preliminary design of large supersonic and subsonic commercial transport aircraft is summarized in Figure 21. It shows that we have a long way to go to achieve the full potential of computerization and that a significant fraction cannot be coded with the present state of the art. Examination of the detailed and final design phases and of this or other vehicles would show a similar picture. Therefore, many gaps must be filled before we can have a fully effective automated design capability. It is also clear, however, that some analyses used in the design process and the extensive testing required will never be completely automated.

A basic objective in the implementation of an IPAD system is the exploitation of the capabilities of a subordinate computing system to enhance the design productivity of a project engineering team. The design environment associated with IPAD will enrich individual participation, encourage more team activity, and encourage greater user creativity. The total work environment will be improved with its principal outside manifestation in a number of IPAD work and management centers or rooms. The particular room illustrated in Figure 22 is an IPAD executive room for engineering and management reviews that is equipped with a variety of remote terminals and display devices to enhance the evaluation of technical and administrative data. Other rooms with different arrangement of equipment would be used as IPAD workrooms in which interdisciplinary teams could create, review, and change design concepts and details in trade-off and optimization studies as well as in individual specialized design activities. The number and type of rooms required depends on the type and level of projects underway at a particular time.

Figure 23 is a photograph of the Mission Control Center at the Lyndon B. Johnson Space Center in Houston, Texas. It uses many of the features expected in an IPAD executive or workroom. Therefore much software and hardware experience applicable to IPAD is available now.

IPAD BENEFITS

The primary benefit expected from IPAD will be an increase in designer productivity from the utilization of system software and design methods that increase technical capability and creativity and reduce cost and flow time. Reinvestment of time and cost savings can provide better products sooner and cheaper and thus insure greater technical depth before product fabrication. The potential benefits of IPAD have been evaluated by studying the time and labor utilized in the design process, by determining the savings experienced with currently available systems such as those listed on Figure 12, and by estimating the extension of such savings on small tasks to the whole system design task in a large organization. The results are presented in Figure 24 where a range of values are given because characteristics of design projects differ. Manpower costs are classified as technical management, technical judgment, and technical routine with the latter two divided into subgroups. The current distribution of effort and that in IPAD are given along with the estimated cost savings. Note that, as expected, the largest savings accrue in technical routine with no cost savings anticipated in technical management. Total cost savings are estimated at 20% to 60%, depending on the project, with 25% to 90% savings in flow time.

Design productivity trades available to the IPAD user are illustrated in Figure 25. Cost, flow time, and design quality are plotted on three orthogonal axes with an arrow projecting from the origin to indicate a particular combination selected for a design project using current methods. If IPAD could be used, the chief designer would have the additional options indicated by the three other arrows. For the same cost and time, he could increase design quality (vertical arrow) and thereby reduce his company risk in the development of his product. Alternatively, he could reduce cost or flow time for the same design quality (right and left arrows) or he could select some other combination. Thus, IPAD can provide new opportunities to increase the productivity of a design staff in the highly competitive, tight budget environment that exists today.

The development of systems such as IPAD will continue for many years but leave room for even more automation. In addition, the availability of such tools will change the nature of the design process and identify other needs and opportunities for improvement. To prepare ourselves we should conduct research on the design process itself as well as research on design technology. We must learn more about combining men and machines in organizations that will produce the best design quickly and economically. Research on the design process must consider both technical and social factors if we are to reach our optimum design goal. The technical side of new analyses, synthesis methods, and computer hardware and software, is clear-cut. The social part is only partly understood today. A large design organization is a dynamic social system that cannot be managed well without knowledge of the social forces that constantly buffet it. Such knowledge will become more important in the future as members of the design team become increasingly concerned about competition with the computer. More technology is available today for design automation than the social side will accept, References 1 and 19.

CONCLUDING REMARKS

Great progress has been made in the computerization of analysis. Computerization of design is underway and the time and technology are right for exploiting this emerging field. However, design automation must emphasize computer application for enhancing communications and management as well as calculations. Speeding the flow of information (data and decisions) is the next contribution that will enable big design organizations and their man-computer teams to design better, faster, and cheaper. NASA-industry studies have identified an IPAD system that can be developed from existing technology to provide the desired benefits. Additional research on the design process is needed to tell us how to arrange future man-to-man and man-to-computer interfaces to accomplish even more. Surely, automation will increase and gradually change the characteristics of the design process and the designers involved. Certainly any organization that plans to be a leader in design of advanced vehicles and systems of the future must be the leaders in the development and application of automated design processes.

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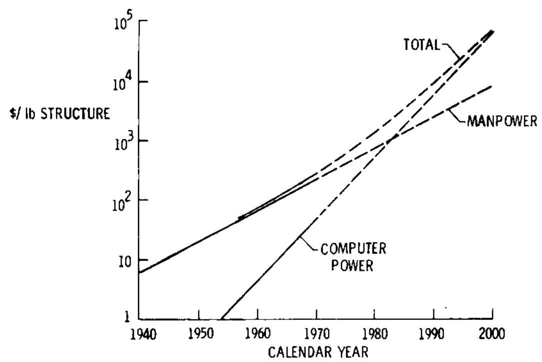

Figure 1. Aircraft structural design costs per pound.

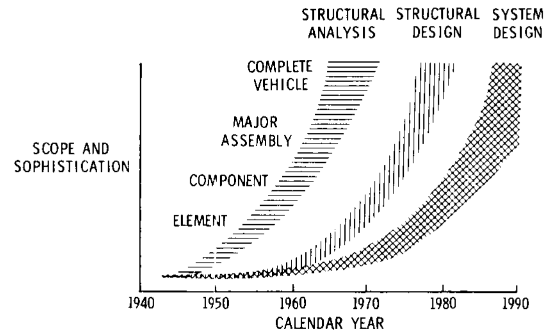

Figure 4. Growth of analysis and design automation.

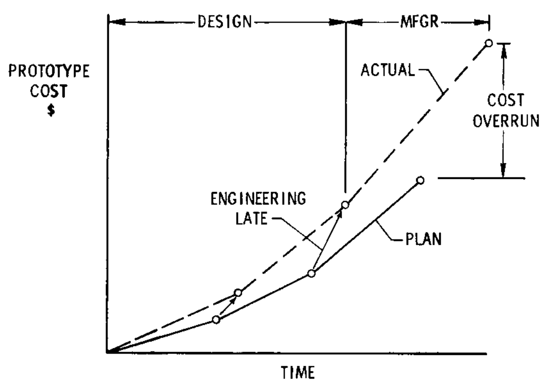

Figure 2. Cost impact of untimely engineering.

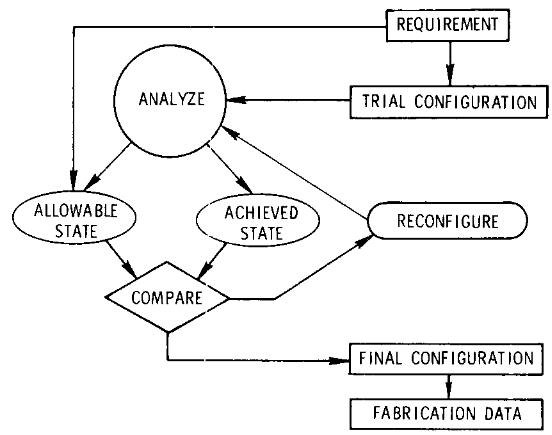

Figure 5. The basic design process.

CHARACTERISTICS OF ADVANCED AEROSPACE VEHICLES

- BIG, COMPLEX, SOPHISTICATED, EXPENSIVE
- INCREASED PERFORMANCE AND ECONOMY
- SENSITIVITY TO STRUCTURAL WEIGHT, ETC.

NATURE OF DESIGN PROCESS FOR LARGE VEHICLES

- COMPLICATED, EXPENSIVE, TAKES A LONG TIME
- MULTITUDE OF DESIGN CRITERIA, DATA, CALCULATIONS
- HIGH RISK OF POOR QUALITY, COSTLY CHANGES

CHARACTERISTICS OF BIG DESIGN STAFFS

- NUMEROUS PEOPLE, INTERFACES, COMMUNICATIONS
- MANAGEMENT COMPLEX AND DIFFICULT

Figure 3. Problems of the design process.

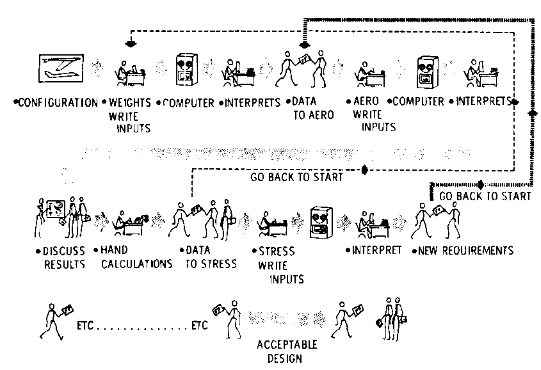

Figure 6. Current design procedures.

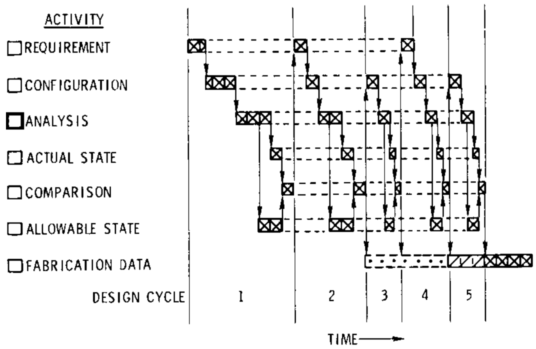

Figure 7. Design process in the time domain.

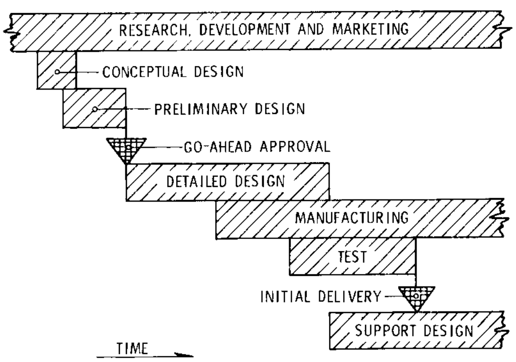

Figure 8. Aerospace product development.

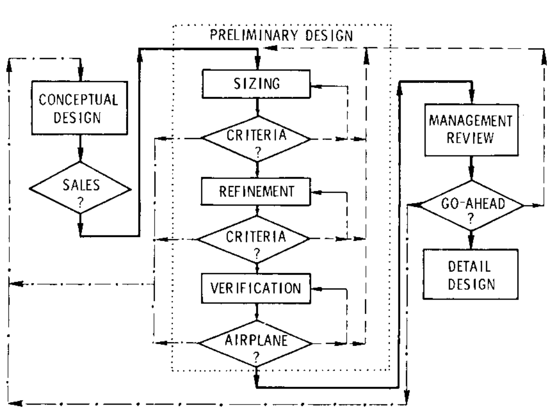

Figure 9. A design decision network.

	CONCEPTUAL	PRELIMINARY	DETAILED
• MANPOWER	1 - 5	10 - 200	300 - 2000
• FLOWTIME	1 - 4 WK	3 - 12 MO	1 - 5 YR
• CONFIGURATIONS EXAMINED	30	150	1
• WEIGHT ACCURACY	<92	92 - 98	>98%
• OBJECTIVE	DEFINE MARKET POTENTIAL	SELECT ACCEPTABLE AIRPLANE	PREPARE MANFACTURING & TEST PLANS
• OUTPUT	POTENTIAL AIRPLANE CONCEPT	VERIFIED AIRPLANE CONFIGURATION	SHOP DATA AND DRAWINGS

Figure 10. Definition of design levels.

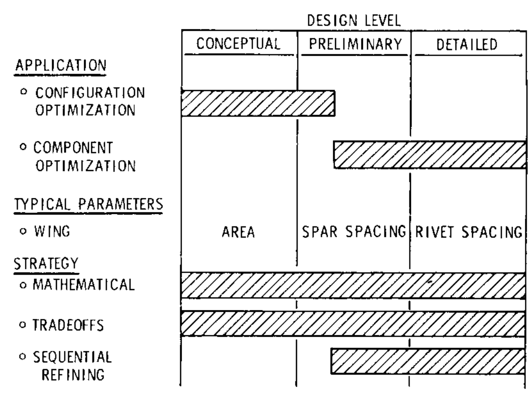

Figure 11. Optimization application and strategy.

CONCEPTUAL VEHICLE SYNTHESIS

ACSYNT	NASA - AMES
ADAM	McDONNELL DOUGLAS
AVSYN	RYAN TELEDYNE
CADE	McDONNELL DOUGLAS
CPDS	BOEING
ICAD	USAF - ASD
ODIN	AEROPHYSICS - NASA - USAF
SYNAC	GENERAL DYNAMICS

COMPUTERIZED STRUCTURAL ANALYSIS

NASTRAN	NASA-LANGLEY
ASKA	U OF STUTTGART
FORMAT	USAF-FDL

AUTOMATED STRUCTURAL SIZING

ASD	McDONNELL DOUGLAS
ASOP	GRUMMAN
FADES	NASA - LANGLEY
SPAR	LOCKHEED

INTEGRATED LOADS AND STRUCTURES

ANALYSIS

ATLAS	BOEING
FAMAS	LOCKHEED
IDEAS	GRUMMAN

SIZING

ARROW	McDONNELL DOUGLAS
RRAPID	NORTH AMERICAN
DAWNS, SAVES, SWIFT, WIDOWAC	NASA - LANGLEY

Figure 12. Progress toward automated design in aerospace.

U. S. ARMY

- INTEGRATED WEAPONS SYSTEMS SYNTHESIS MODEL (IWSSM) INCLUDES SEVEN COMMODITY CLASS (GUN, VEHICLE, ETC.) VERSIONS

U. S. NAVY

- COMPUTER-AIDED DESIGN ENVIRONMENT (COMRADE)
- INTEGRATED SHIP DESIGN SYSTEM (ISDS)

U. S. MARITIME ADMINISTRATION

- COMPUTER AIDS TO SHIPBUILDING

ARCHITECTS

- ARCHITECTURE MACHINE (URBAN 5)
- COMPUTER-AIDED MODEL FOR ARCHITECTURAL DESIGN (SYNARC)
- SPATIAL ALLOCATION IN DESIGN AND PLANNING (ALOKAT)

CIVIL, BRIDGE & STRUCTURAL ENGINEERS (US & UK)

- COMPUTER-AIDED BUILDING DESIGN SYSTEM
- COMPUTER SYSTEMS FOR BUILDING PLANNING AND DESIGN
- INTEGRATED CIVIL ENGINEERING SYSTEM (ICES)

Figure 13. Progress toward automated design outside aerospace.

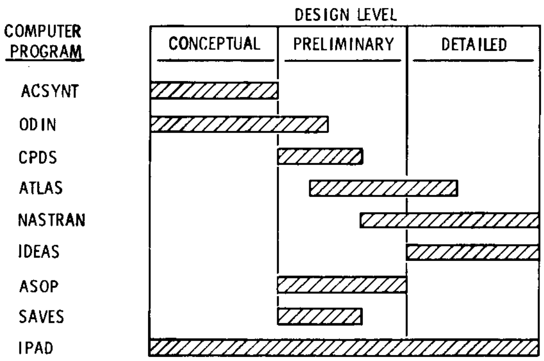

Figure 14. Relationship of aerospace computer programs to design levels.

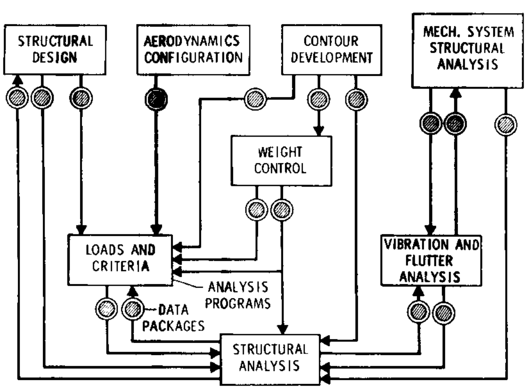

Figure 15. Grumman Integrated Design Analysis System (IDEAS).

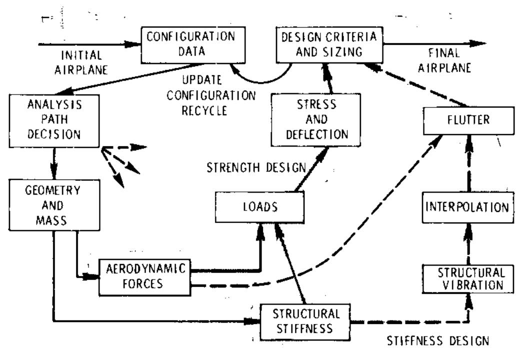

Figure 16. Boeing Integrated Analysis System (ATLAS).

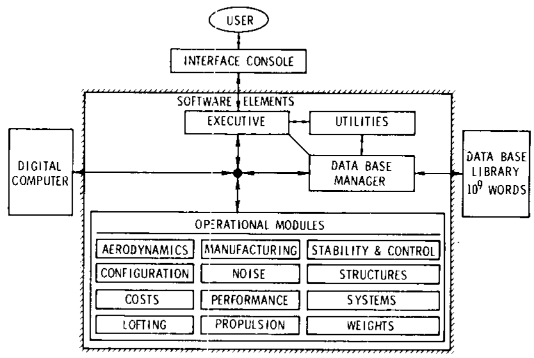

Figure 17. NASA Integrated Programs for Aerospace-Vehicle Design (IPAD).

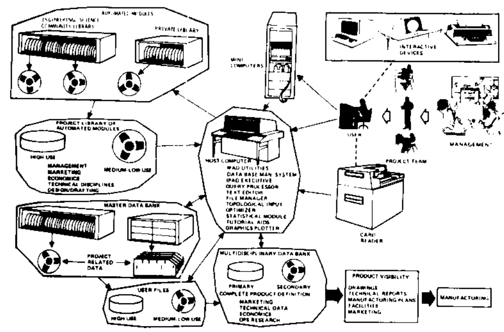

Figure 18. IPAD overview.

- MULTIDISCIPLINARY ENGINEERING DESIGN TOOL TO INCREASE THE EFFECTIVENESS, ECONOMY AND SPEED OF THE DESIGN PROCESS AND ITS MANAGEMENT
- FLEXIBLE, VERSATILE, AND OPEN-ENDED SYSTEM OF INTEGRATED, MODULAR COMPUTER PROGRAMS FOR DESIGN:
  - OF A VARIETY OF VEHICLES OR SYSTEMS
  - AT VARIOUS LEVELS, SCOPES, AND DEPTHS OF DESIGN
  - WITH USER ORIENTED LANGUAGE, CONTROL, AND RESPONSE
- REASONABLE INITIAL CAPABILITY IN A COMPUTER-AIDED TOOL WITH GROWTH POTENTIAL TO A COMPREHENSIVE, DYNAMIC SOFTWARE/HARDWARE SYSTEM

Figure 19. Objectives of IPAD.

SYSTEM DEFINITION

- TWO CONTRACTUAL FEASIBILITY STUDIES (MARCH 1972 - SEPT. 1973)
  - √ DEFINE A FEASIBLE SYSTEM
  - √ DEFINE A COMPUTER SOFTWARE SYSTEM DESIGN
  - √ ASSESS COSTS, SCHEDULES, BENEFITS, AND IMPACTS
- EVALUATE SYSTEM WITH INDUSTRY PARTICIPATION (1973-74)

SYSTEM DEVELOPMENT

- DEVELOP CORE SOFTWARE (1975-80)
  (EXECUTIVE, DATA BASE MANAGER, UTILITIES)
- COLLECT AND DEVELOP SELECTED OPERATIONAL MODULES (1970 →)
- CHECKOUT AND RELEASE TO INDUSTRY (1980)

Figure 20. Status and plans of IPAD.

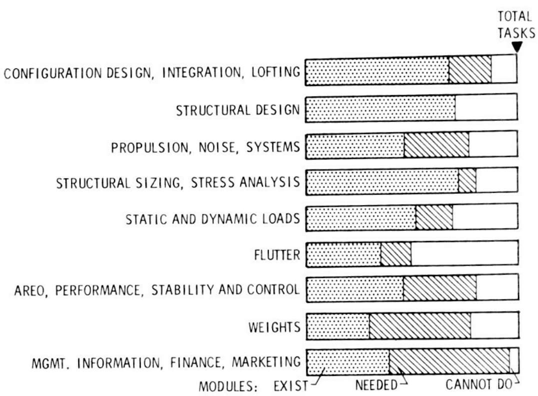

Figure 21. Technical capability for automated preliminary design of subsonic and supersonic commercial transports.

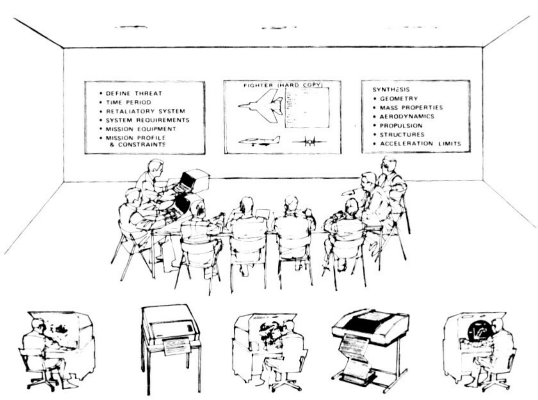

Figure 22. IPAD executive room.

Figure 23. Mission control at NASA-JSC.

MANPOWER COST	DISTRIBUTION OF EFFORT CURRENT	DISTRIBUTION OF EFFORT IPAD	IPAD SAVINGS
□ TECHNICAL MANAGEMENT	6	10 - 15	0%
□ TECHNICAL JUDGEMENT	34	35 - 65	20%
• PROCEDURE DEVELOPMENT	12		
• CALCULATIONS	9		
• RESULTS EVALUATION	13		
□ TECHNICAL ROUTINE	60	55 - 20	25 - 90%
• INFORMATION EXCHANGE	26		
• DATA PREPARATION	34		
◇ TOTAL	100	100	20 - 60%
FLOWTIME			25 - 90%

Figure 24. Potential savings from IPAD.

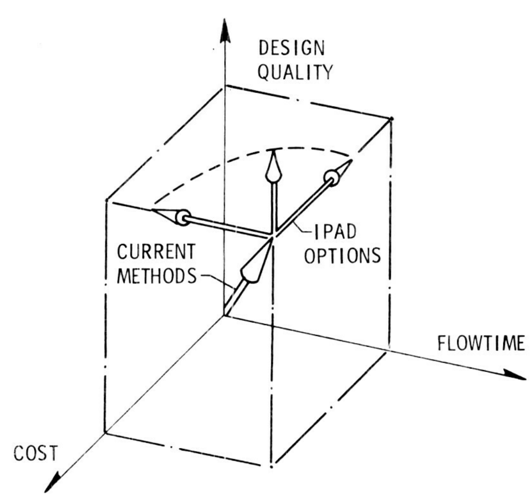

Figure 25. IPAD design productivity trades.